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*Published in:*
Gerlands Beitrage zur Geophysik

*Publication date:*
1989

*Document version*
Early version, also known as pre-print

*Citation for published version (APA):*
Artemieva, I., & Gliko, A. O. (1989). Geophysical conditions and the mechanism of the Tien Shan Cenozoic uplift. *Gerlands Beitrage zur Geophysik*, *98*(2), 1-13.

ISSN 0016-8696 • Gerlands Beitr. Geophysik • Leipzig • 98 (1989) 2 • S.101—113

# Geophysical conditions and the mechanism of the Tien-Shan Cenozoic uplift

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With 8 Figures

Received January 12, 1988

## Summary

The upper mantle of the Tien-Shan possesses anomalous features, namely lowered velocities and increased attenuation of seismic waves; the lithosphere is considerably thinned. The region is characterized by strong negative BOUGUER and long-wave free-air gravity anomalies the cause of which clearly appears to be within the mantle. A model of thermal thinning of the lithosphere is considered as a mechanism of the Tien-Shan Cenozoic uplift. The heat flow from the anomalous mantle is calculated on the basis of data of the Cenozoic vertical movements of the Tien-Shan. A qualitative model of the process is proposed.

## Zusammenfassung

Der obere Mantel des Tien-Shan besitzt anomale Merkmale, wie verminderte Geschwindigkeit und erhöhte Dämpfung seismischerWellen; die Lithosphäre ist wesentlich verdünnt. Diese Region ist durch starke negative BOUGUER- und langwellige Schwereanomalien gekennzeichnet, deren Ursprung eindeutig innerhalb des Mantels zu liegen scheint. Das Modell thermischer Verdünnung der Lithosphäre wird als Mechanismus der känozoischen Hebung des Tien-Shan betrachtet. Der Wärmefluß aus dem anomalen Mantel wird auf der Grundlage von Daten der känozoischen Vertikalverteilung des Tien-Shan berechnet. Es wird ein qualitatives Modell dieses Prozesses vorgeschlagen.

## Резюме

Верхняя мантия Тянь-Шаня имеет аномальные свойства, т.е. уменьшенную скорость и повышенное затухание сейсмических волн. Литосфера существенно утонена. Регион характеризуется сильно негативными аномалиями Буже и длинноволновой тяжести, которые очевидно возникают внутри мантии. Модель термического утончения рассматривается как механизм кайнозойского поднятия Тянь-Шаня. Поток тепла из аномальной мантии определяется на основе данных кайнозойских вертикальных движений Тянь-Шаня. Предлагается качественная модель процесса.

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## 1. History of the Tien-Shan vertical movements

A geosyncline stage of the Tien-Shan development completed by a folded mountain system formation ended about 220 MY ago, and during the Mesozoic and almost the whole Paleogene the Tien-Shan was characterized by predominance of platform conditions. The neotectonic activation of vertical movements began in the Late Paleogene (Oligocene), 25-30 MY ago, with the average uplift of the whole territory being about 2.7 km (ARTEMIEV and BELOUSOV 1980). The average uplift of the Tien-Shan ridges is 5 km and more (CHEDIYA 1972, NESMEYANOV 1967).

The velocity of Cenozoic vertical movements gradually increased and became maximal in the Holocene (Fig. 1). However, velocity variations obtained for the Holocene may not be very reliable. They may be a result of the existence of a short-period component in a spectrum of vertical movements, the influence of which is being suppressed during the determination of average uplift velocities for essentially longer time intervals preceding the Holocene.

The stage of the latest Tien-Shan orogenesis is characterized by intensive contrast vertical movements in blocks. Folded forms have subordinate meaning, and are developed mainly in a sedimental cover and in depressions (CHEDIYA 1972).

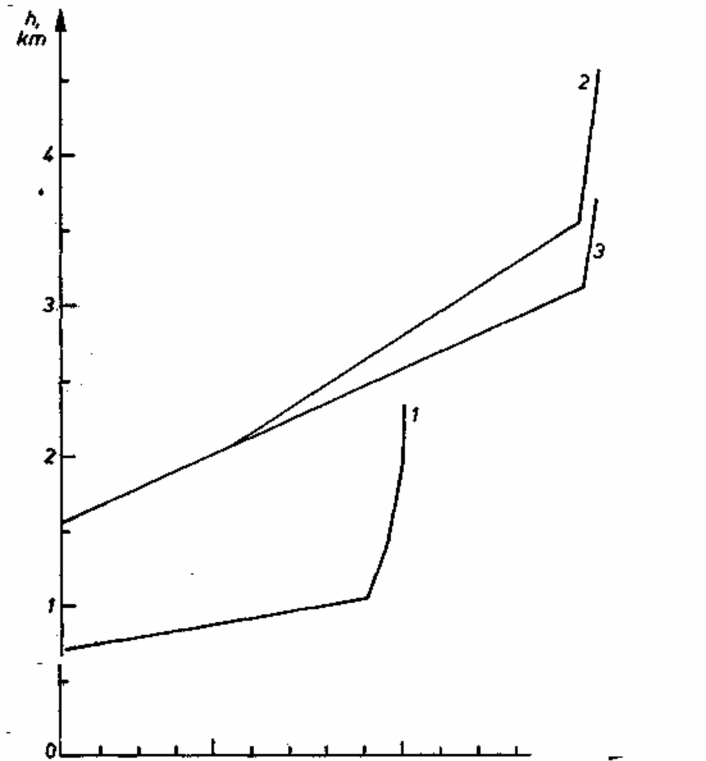

Fig. 1. Uplift of the Tien-Shan calculated on the basis of uplift velocities. *1* from ARTEMIEV and BELOUSOV (1980), 2 from CHEDIYA (1972), 3 from NESMEYANOV (1967). Curve *1* shows average uplift of the whole territory, curves *2* and 3 show average uplift of ridges. The initial uplift was assumed to be 0.0 km, 0 MY corresponds to the beginning of the rejuvenation process.

A characteristic feature of the latest Tien-Shan tectonic movements is their inheritance: a development of troughs and uplifts in Mesozoic and Cenozoic time trended in the same direction as in Paleozoic time (KRESTNIKOV 1962). This phenomenon can be explained by horizontal heterogeneities of a lower lithosphere existing from ancient times, and by intertia of the thermal regime (VINNIK 1976). Recent troughs of the Tien-Shan coincide with relics of the relatively cold, heavy, and thick lower lithosphere.

## *2.* Structure of the Earth's crust and the upper mantle beneath the Tien-Shan

The crust thickness beneath the Tien-Shan is 45-60 km (Fig. 2), it is thicker below ridges and thinner below depressions. Blocks with different crust thickness are divided by deep faults. An increase of the crust thickness below ridges occurs mainly at the expense of a "basalt" layer increase. The thickness of a "basalt" layer of the crust beneath the ridges of the Northern Tien-Shan amounts to 40 km while a "granite" layer has only 10 km thickness. Below depressions of the Tien-Shan corresponding thicknesses are 25 and 20 km (BELOUSOV 1962).

Seismic data (VINNIK 1976) show that the lithosphere beneath the Tien-Shan is greatly thinned, and the lower lithosphere may generally be absent in quickly uplifting blocks. At present, the lithosphere thickness beneath the Tien-Shan does not

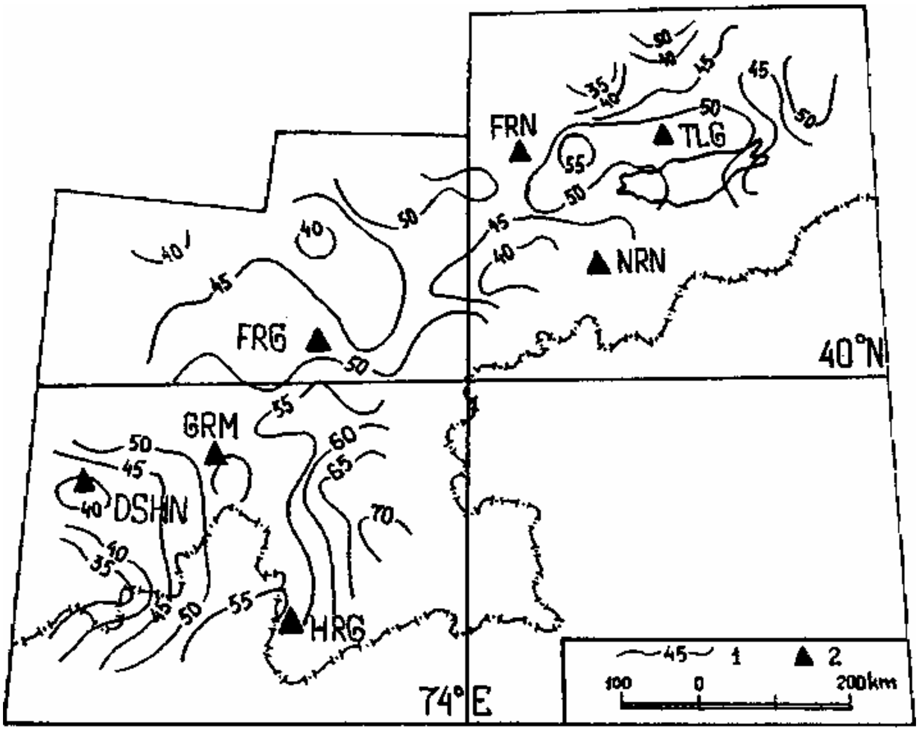

Fig. 2. Crust thickness of the Tien-Shan (LUKK et al. 1983).
1 isolines of crust thickness [km], *2* some seismic stations

exceed 60-80 km, and before the stage of neotectonic activation it was evidently about 120-150 km which is typical for regions of Hercynian stabilization. According to the seismic data the upper mantle surface beneath the Tien-Shan is not flat.

## 3. Seismic data

Seismic data show the existence of clearly expressed inhomogeneities in the under-crust layers of the region. By the upper mantle properties the region of Cenozoic uplift of the Tien-Shan is divided into two parts, the boundary between them coinciding approximately with the Talas-Fergana fault (LUKK et al. 1983). The north-eastern Tien-Shan is characterized by positive residuals of seismic waves and their low velocities; a clear correlation between a value of surface uplift and residuals of seismic waves exists in this region. It is assumed that the upper mantle beneath the eastern Tien-Shan is anomalously hot (VINNIK and SAIPBEKOVA 1984). The negative residuals of seismic waves, typical for stable platforms with a cold upper mantle, have been obtained for the southwestern Tien-Shan (Fig. 3).

In general, the Tien-Shan is characterized by increased attenuation of seismic waves. Zones of high attenuation coincide with areas mostly tectonically active in Quaternary time or with the areas of deep faults.

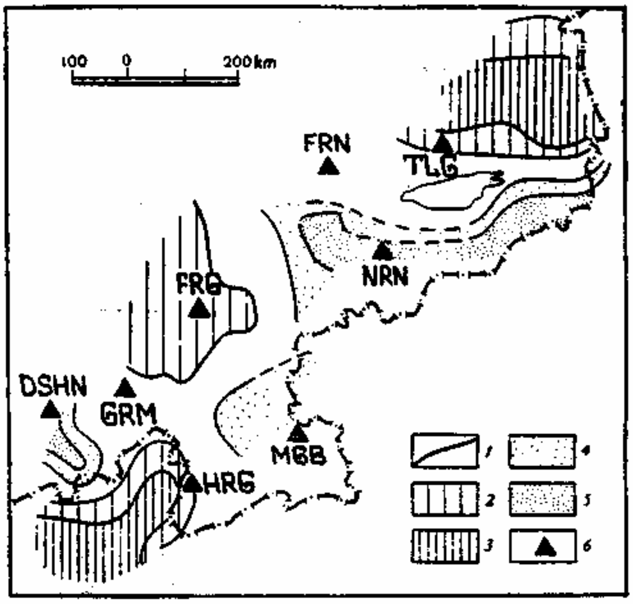

Fig. 3. Structure of the Middle Asia upper mantle according to seismic data (LUKK et al. 1983).
*1* $\delta V$-isolines, *2, 3* regions of increased upper mantle velocities, *4, 5* regions of decreased upper mantle velocities, *6* seismic stations

## 4. Gravity data

The results of the Tien-Shan gravity studies as well as seismological data show that the density of the undercrustal layer in the blocks that have undergone an intensive uplift is decreased. So-called mantle anomalies (gravity anomalies obtained after gravity influence of the crust base has been eliminated) are positive in depressions and negative in high-elevated areas of the Tien-Shan (Fig. 4) (ARTEMIEV 1975).

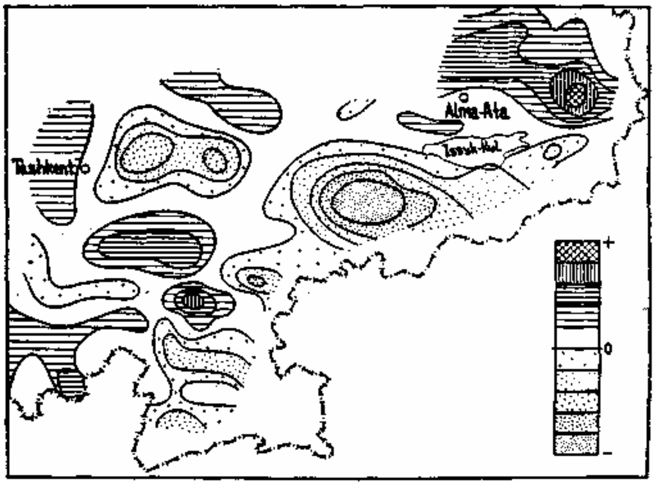

Fig. 4. Scheme of mantle gravity anomalies for Middle Asia (ARTEMIEV 1975)

The region of the Tien-Shan neotectonic activation is close to the isostatic equilibrium, however no more than 2/3 of the compensation may be explained by the crust thickness variations. About 1/3 of the compensation is provided by a lithosphere density decrease. The low-density area is located between Moho and the depth of 70-90 km (GOLLAND 1981).

During Mesozoic and Paleogene time the Tien-Shan was characterized by predominance of platform conditions, and hence it may be considered that at that time the crust of the region was in a state of an isostatic equilibrium. It is known that the crust thickness of high density blocks exceeds the crust thickness of less density, granitized blocks under the isostatic condition of platform areas. However, at present the reverse relation is typical for the Tien-Shan. Therefore, the contemporary relief of the Moho surface was formed as a result of intensive tectonic Neogene-Quaternary movements. Thus there might exist a close connection between processes that cause a Moho-surface deformation and vertical movements of the day surface.

Gravity investigations revealed a strong minimum of BOUGUER anomalies in the regions of Central and Middle Asia. The same region is characterized by strong negative long-wave isostatic anomalies and long-wave free-air anomalies pointing to a significant decrease of upper mantle density at the depths exceeding the level of isostatic compensation in the asthenosphere (ARTEMIEV and GOLLAND 1982).

## 5. Heat-flow data

Because of the complicated orography of the Tien-Shan, measurements of heat-flow in the region were carried out on the whole in the intermontane depressions. The Tien-Shan is characterized by strongly differentiated heat-flow with values changing from 20 to 100 mW/m$^2$ and more (LUBIMOVA 1978).

Zones with very high heat-flow coincide with regions that are characterized by low seismic wave velocities and with regions for which negative isostatic anomalies have been obtained. This observation is in good agreement with data on depths at which melting temperatures are exceeded. In depressions, melting points are exceeded at depths of 120-150 km, beneath the ridges at depths of 30-50 km.

The field of mantle heat-flow is also strongly differentiated. Minimal values were obtained for depressions (4-15 mW/m$^2$), maximal ones for zones of high ridges and deep faults (35 mW/m$^2$). The Moho discontinuity is not isothermal, the temperature difference may be about 500 °C for different tectonic structures. It indicates a non-stationary regime of the upper mantle (ARSHAVSKAYA 1985).

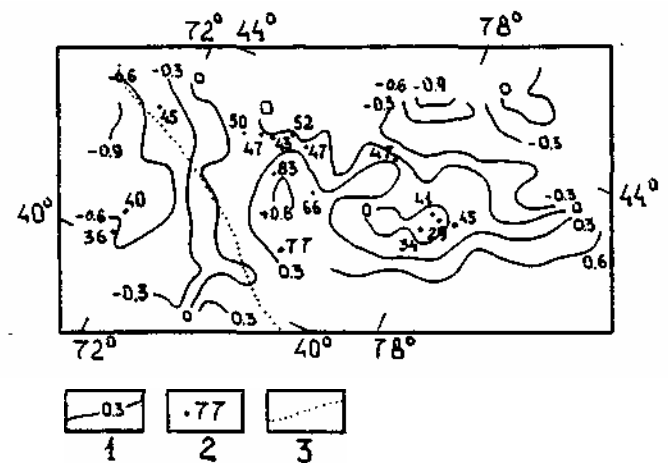

Fig. 5. The residuals of seismic waves *(1)* and heat-flow data in mW/m$^2$ *(2)* for the Tien Shan, *3* location of Talas-Fergana deep fault (VINNLK and SAIPBEKOVA 1984)

## 6. The model

The existence of a vast regional gravity minimum over the Central Asia region of neotectonic activation, part of which is the Tien-Shan, as well as seismic data allow us to assume the existence of an enormous volume of anomalous material in the upper mantle, this material being of reduced density and increased temperature. The lithosphere of the Tien-Shan is thinned to 50 % during the time of Cenozoic activation. Thus, a thermal model of lithospheric thinning, which has been examined by different authors (CROUGH and THOMPSON 1976, GLIKO and ROVENSKIH 1982, 1985, SPOHN and SCHUBERT 1982, 1983), may be considered as a possible model of the Tien-Shan formation.

In the frames of the model a hot, partly melted material of the anomalous mantle is injected into the asthenospheric layer and carries out to it a great amount of heat. The lithospheric structure formation is seen as a process of replacement of lithospheric lower parts by more hot and less, dense upper mantle material, when the lower parts of the lithosphere are heated to a characteristic temperature corresponding to an abrupt decrease of viscosity. The necessary conditions for this process are the existence of density inversion on the lithosphere — anomalous mantle boundary and large enough viscosity of the lithosphere ($>10^{23}$ P). In case of a low-viscous lithosphere a RAYLEIGH-TAYLOR instability (NEUGEBAUER 1983) will play the leading role in the evolution of the system. As the stage of the Tien-Shan neotectonic activation was preceded by a stage of platform development, it is possible to assume that before the process of activation the lithosphere of the region was cold and possessed a high enough viscosity. Thus an abrupt growth of heat-flow on the lower lithospheric boundary caused an upwards displacement of this boundary that is very likely a solidus boundary for mantle material. For all this, a Cenozoic uplift of the Tien-Shan may be to a marked degree explained as a result of isostatic vertical movements of the lithospheric blocks. Some part of the uplift may result from the thermal expansion of a heated lithosphere.

### 7. Formulation of the problem

Let us assume that before the process of activation, there existed a steady state heat regime $T_0(z)$ in the considered region. Under this assumption the lithosphere thickness $\xi_0$ was defined by radiogenic heat sources in the crust $H(z)$ and by a value of steady state heat-flow on the lower lithospheric boundary $Q_0$. We assumed that a temperature on this boundary is equal to a solidus temperature of mantle rocks at the same depth $T_0(\xi_0) = T_m$.

When the process of neotectonic activation starts, an infringement of the stationary heat regime takes place. An intrusion of large hot masses of the anomalous mantle to the bottom of the lithosphere causes an increase of heat-flow on the lower boundary of the lithosphere. A lithosphere thickness evolution is determined by the solution of the next problem for a heat-conductivity equation with a condition on a moving boundary $\xi(t)$:

$$\begin{aligned}
&\frac{\partial u}{\partial t} = a^2 \frac{\partial^2 u}{\partial z^2} + H(z) \\
&u(z,0) = T_0(z) \\
&u(0,t) = 0 \\
&u(\xi(t),t) = T_m(\xi(t)) \\
&-\chi \frac{\partial u}{\partial z}(\xi(t),t) + Q(t) = -\lambda\rho \frac{d\xi}{dt}
\end{aligned} \qquad (1)$$

where $u(z, t)$ is a temperature distribution in the lithosphere, $H(z)$ - heat generation in the crust, $\chi$ - thermoconductivity, $a^2$ - thermal diffusivity, $\xi(t)$ - thickness of the lithosphere, the $z$-axis is directed vertically downwards. The last equation is an energy balance on a lithosphere - anomalous mantle boundary: the heat lost by an anomalous mantle is spent for a lithosphere heating to the solidus temperature and for its partial melting.

The solution of problem (1) allows to determine an evolution of lithosphere thickness $\xi(t)$ when a heat flow from the anomalous mantle $q(t) = Q(t)/Q_0$ is known. However, as a function $q(t)$ is not known a priori, most of the authors who have analysed the problem studied the simplest case of step change of a mantle heat flow in time (CROUGH and THOMPSON 1976, SPOHN and SCHUBERT 1982, 1983). We have proposed a new approach for the estimation of a deep thermal regime of the areas of neotectonic activation based on the data of the vertical crust movements in the considered region (ARTEMIEVA and GLIKO 1986). In the case when isostatic compensation of the uplift is partly due to the anomalous masses of reduced density lying in the upper mantle then a part of the whole uplift is an isostatic response of the system to the lithosphere thinning and the anomalous mantle thickening.

The amplitude of the vertical crust movements $h(t)$ is related to the lithosphere thickness by:

$$h(t) = h_e(t) + h_{cr}(t) + \frac{\Delta\rho}{\rho}(\xi_0 - \xi(t)) + \frac{1}{3}\alpha \int_0^{\xi(t)} u(t,z)dz \tag{2}$$

Here $h_e(t)$ is the amplitude of an isostatic uplift due to surface erosion, $h_{cr}(t)$ - the amplitude of an isostatic uplift due to crust thickening. The last term describes an uplift caused by thermal expansion of lithospheric material ($\alpha$ - coefficient of thermal expansion).

Eqs. (1) and (2) may be used to determine an evolution of the lithosphere thickness $\xi(t)$ and a heat-flow from the anomalous mantle $q(t)$ when the data on vertical movements of the crust are available and the corrections $h_e$ and $h_{cr}$ can be calculated.

The numerical solution of the problem was carried out in accordance with a modified BUBNOV-GALERKIN method (MELAMED 1958). The essence of the method is that the initial problem is reduced to the infinite system of ordinary differential equations and the shortened system is solved. For this, a solution of a non-dimensional problem obtained from eqs. (1) by substitution $\xi = z/\xi_0$, $\tau = t/\tau_0$ is represented as the sum:

$$u(z,t) = v(z,t) + \varphi(t)\frac{\xi(t) - z}{\xi(t)}, 0 < z < \xi(t).$$

Function $v(z, t)$ is expanded into the FOURIER series on the segment $[0, \xi(t)]$ with coefficients $A_k$ when time $t$ is fixed. Substitution of this equation to the problem (1) gives:

$$A_k' = -\left(\frac{k\pi}{\xi}\right)^2 A_k - \xi'\left(\frac{2k}{\xi}\sum_{i=1}^{\infty} A_i W_{ik}\right) \tag{3}$$

$$\xi' = \frac{1}{\alpha}\left[\frac{2\pi}{\xi^2}\sum_{i=1}^{\infty} iA_i(-1)^i - qR\right], \qquad W_{ik} = \begin{cases} (-1)^{i+k+1}\dfrac{i}{i^2 - k^2}, & i \neq k \\ -\dfrac{1}{4k}, & i = k, \end{cases}$$

where $R = \dfrac{Q_0}{\chi T_m / \xi_0}, \alpha = \dfrac{\lambda}{cT_m}$ - the Stefan number which characterizes a part of heat that is spent for a partial melting of lithospheric material (λ is the latent heat of fusion of the lower lithosphere material, *c* — heat capacity).

## 8. The results of numerical modelling

The parameters determining the model were the next: the thickness of the lithosphere before neotectonic activation (25-30 MY ago) was equal to 120 and 150 km; temperature difference on the upper and lower lithospheric boundaries $\Delta T$ = 1300 °C; melting-curve gradient in the lower lithosphere grad $u_m$ = 2.5 °C/km; steady state temperature gradient on the lower lithospheric boundary grad $u_0$ = 6.0 °C/km; heat capacity $c$ = 1.4 X $10^3$ J/°C; thermal diffusivity $a^2 = 10^{-6}$ m$^2$/s; heat of fusion $\lambda$ = 10 cal/g; the characteristic time of lithosphere heating $\tau_0 = \xi^2_0/a^2$ was equal to 456 MY and 713 MY for $\xi_0$ = 120 and 150 km.

The data on the amplitudes of .the crust vertical movements for which the calculations were carried out are represented in Fig. 1. When calculating the correction $h_e(t)$ for the curve *1,* the velocity of surface erosion was assumed to be 2 mm/y for the period of abrupt uplift (last 1 MY) and 0.2 mm/y for the preceding period of activation. (Analogous assumptions were made for the other curves.) Then for the whole stage of neotectonic activation $h_e$=0.75-0.85 km. When calculating the correction $h_{cr}(t)$ it was assumed that from the Neogene 1/3 of isostatic compensation took place due to the crust thickening. Then for the end of the Holocene $A_{cr}$ = 0.7-0.8 km. Fig. 6 represents the lithosphere thinning curves for the next models: *la* - for curve *1* (Fig. 1) without consideration of surface erosion and assuming that all isostatic compensation is due to the lithospheric thickness changes; the other curves (their

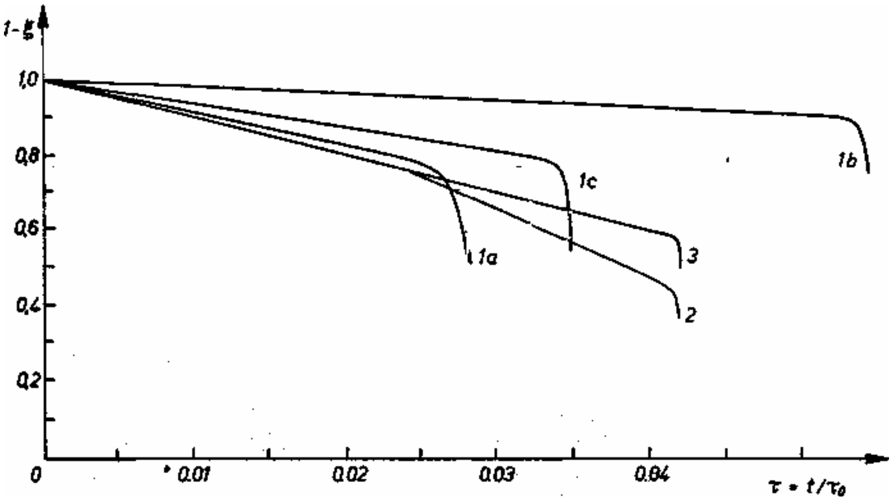

Fig. 6. Evolution of lithosphere thickness. The numbers of the curves correspond to those in Fig. 1. Curves 1*a, b* for $\xi_0$ = 120 km, other for $\xi_0$ = 150 km. Density of the lid $\rho$ = 3.35 g/cm$^3$; density of the anomalous mantle $\rho_1$ = 3.30 g/cm$^3$ for curves 1*a, b, c;* $\rho_1$ = 3.23 g/cm$^3$ for *2, 3.* Thermal diffusivity $a^2 = 10^{-6}$ m$^2$/s ($a^2 = 0.5 \cdot 10^{-6}$ m$^2$/s for curve 1*a)*

numbers correspond to those in Fig. 1) for the cases when corrections $h_e$ and $h_{cr}$ were included.

The following remarks must be made with respect to the correction $h_{cr}(t)$. Evidently, only two mechanisms may provide a crust thickening beneath the Tien-Shan mountain system. 1. An intrusion of basalt melts and their crystallization underneath the crust. However, under the conditions of compression typical for the Tien-Shan and being observed in a regional stress field such crust thickening from below may have taken place evidently at the latest stage of activation when the top of the anomalous mantle had reached the depth of 60-80 km. 2. An development of phase changes eclogite (or rocks of granulite facies of metamorphism) -> basalt which may efficiently take place only under high enough temperatures (800 °C) (AHRENS and SCHUBERT 1975, ARTYUSHKOV and SOBOLEV 1982). Such temperatures may be achieved underneath the crust only at the latest stages of the process of thermal thinning of the lithosphere. In any case, there is no ground to assume a significant contribution of a term $h_{cr}(t)$ to the general uplift before the Holocene.

As a result of numerical modelling a value $q(t) = Q(t)/Q_0$ was determined, where $Q(t)$ is the heat-flow supplied to the lithosphere bottom from below, $Q_0$ — value of initial mantle heat-flow ($Q_0$ = 10-15 mW/m$^2$).

The results are represented in Fig. 7. For all the parameters of the model the heat flow from the anomalous mantle increases gradually. Abrupt growth corresponds to the latest $10^4$ - $10^5$ years. Thus the abrupt increase of uplift velocities at this time interval cannot be explained by the corresponding increase of heat flow from the anomalous mantle as these values are physically unreal. It is logical to assume that just at that time the realization of one of the two (or may be both) mechanisms that lead to thickening of the crust beneath the Tien-Shan has begun.

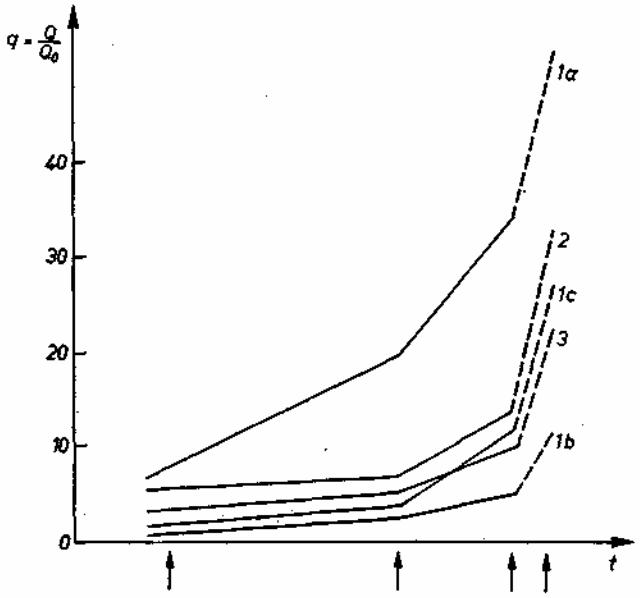

Fig. 7. Calculated mantle heat flow for models in Fig. 6. The ends of the epochs are marked

## 9. A possible mechanism of the Tien-Shan Cenozoic uplift

The results of numerical modelling allow us to see a thermal model as one of the possible models of the Tien-Shan Cenozoic uplift. A number of phenomena typical for the process of neotectonic activation can be qualitatively explained in the frames of the model.

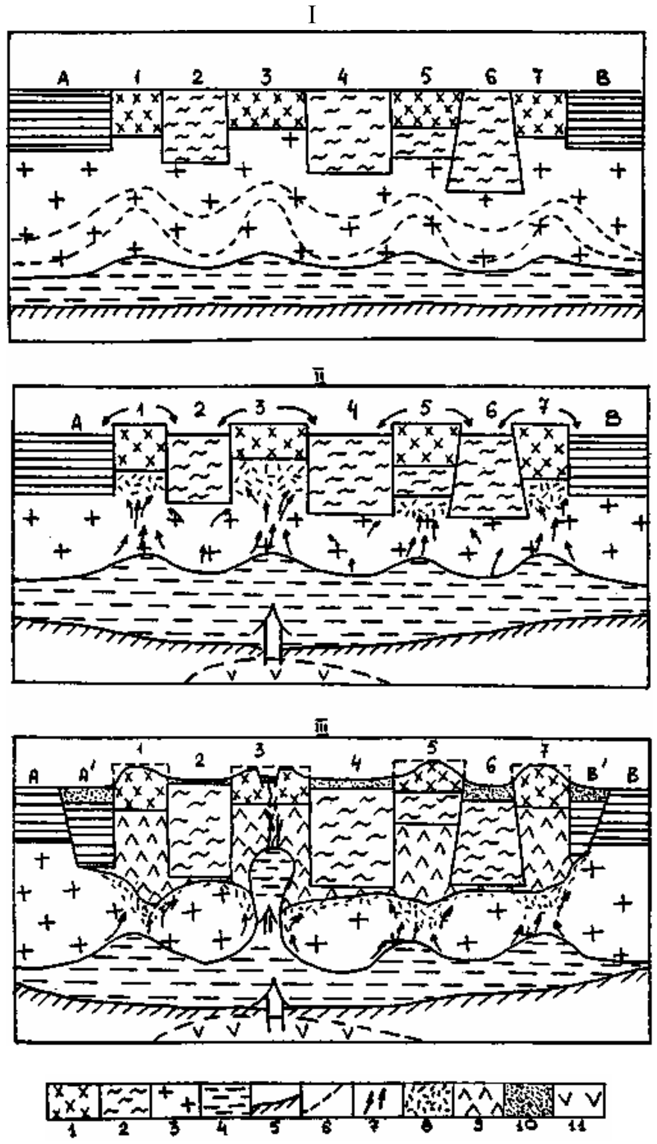

Fig. 8. Qualitative scheme of the Tien-Shan vertical movements development. Numbers on the scheme correspond to different lithosphere blocks.

*1* crust blocks of low density, 2 crust blocks of increased density, *3* lid, *4* asthenosphere, 5 asthenosphere bottom, *6* isotherm, 7 movement of asthenosphere melts to the crust, *8* concentration of melts, *9* new-formed "basalt" layer of the crust, *10* Cenozoic sediments, *11* anomalous mantle

At the first stage of the process (Oligocene-Neogene) (Fig. 8, I) a slow uplift of the boundary takes place, the heat-flow from the asthenosphere to the lithosphere increases. Liquid melts of asthenospheric material rise in the gravity field and are accumulated just underneath the crust. The upper boundary of the asthenosphere is not smooth. It may have uplifts underneath low-density crust blocks that have been granitized at the latest stage of Paleozoic orogeny as, because of the low thermal conductivity of the rocks, thermal heterogeneities of an undercrust layer that have appeared when granitoids have been formed, may be preserved in the lithosphere during many ten millions of years.

At the next stage of the process (Fig. 8, II) an injection of liquid melts into the gradually thinning lithosphere is possible. These melts move to the crust bottom and thicken from below more acid crust blocks. According to the isostatic conditions of platforms, before the activation granitized (i.e. low density) crust blocks were to have a less thickness in comparison with blocks of higher density that divided them. Such relief of the crust lower boundary promoted a concentration of asthenospheric melts underneath blocks of less density. As a result blocks of low density accelerate their isostatic uplift. A differentiated relief, that in general inherits a relief of a Late Paleozoic orogenic system, appears. Differentiation of a relief makes more active the processes of erosion and sedimentation. This leads to an acceleration of an uplift of crust blocks with less density and to a deceleration of an uplift (because of sediment deposition) of more density blocks. In some cases, it may cause their absolute caving. Troughs with a thick layer of sedimentary rocks appear (Fig. 8, III).

The large-scale features of seismic, gravity and heat-fields of the considered region can be easily explained in the frames of the model. Fine features of the Tien-Shan neotectonic structure may be a consequence of the deep process assumed and may be, in particular, caused by a stress field that changed during the process development and was connected with compensational masses redistribution.

## 10. Conclusions

In conclusion, we should like to note that if the considered model of the process of neotectonic activation is true, it may be used for an explanation of the evolution of other regions that are close to the Tien-Shan in tectonic and geophysical features.

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